Name Date

UNIT PROJECT

Designing the Strongest Beam

The safety of a building, bridge, scaffold, piece of machinery, or other structure relies on the design of components, such as beams, within the structure. The strength of a beam depends on the materials used to build the beam and the cross-sectional size and shape of the beam. For example, beams can be rectangular, round, hollow, or open shapes, such as I- or L-beams. Before designing your beam, you will collaborate with your class to determine a standard testing method. The tests will be used to evaluate designs against the required and desired properties of the beams. You will also note the limitations on the beam designs.

For this project, your engineering company needs to design a beam that can support a new apartment building above a large parking area. Each beam will span a large space and support a great deal of weight. Your team will first build and test cardboard models of beams to identify the strongest design(s). The cardboard beams must span at least one meter. Your company’s financial analysts have asked you to keep costs low by minimizing the amount of material per unit length and, in the final steel beams, minimizing the amount of welding or drilling per unit length.

DESIGN CHALLENGE Design, build, test, and optimize a model beam that can support the greatest amount of weight per unit mass of beam material across a one-meter span.

MATERIALS

- safety goggles and leather or work gloves
- cardboard
- materials to support beam on each end
- materials to test strength of beam
- scissors or a craft knife that can cut cardboard
- tape, glue, or other materials to connect cardboard pieces

SAFETY INFORMATION

- Wear safety goggles and leather or work gloves during the setup, hands-on, and takedown segments of the activity.
- Use caution when using sharp tools, which can cut or puncture skin.
- Cut cardboard on a cutting mat or over a lab table.
- When cutting cardboard, always cut away from the body.
- Keep areas where cardboard is being cut clean and tidy. Immediately pick up any items dropped on the floor so they do not become a slip/fall hazard.
- Wash hands with soap and water immediately after completing this activity.

DEFINE THE PROBLEM

1. With your class, do a simple test, and then use the results to set expectations. Set up a strip of cardboard of the type you will be using so that it is about 5 cm wide and spans a distance of 1 m. The test sample should rest on the end supports (such as books or tables) without being fastened. Use string to hang weights from the sample. Set up the test so that the weights do not fall far when the cardboard bends, slips, or breaks. Add weight until the sample breaks or bends an unacceptable amount. Record the mass per unit length of the test sample and your other observations of the test.

2. With your class, use the results of the test to set conditions, such as the maximum mass of a cardboard beam and a starting weight that must be supported. Your class might determine other conditions, such as
   - the maximum amount of sagging and how that will be measured
   - the way the weight will be attached, such as by a broad strap or large cardboard tube
   - a different test, such as keeping the weight constant and increasing the span
   - restrictions on the glue or other materials that can be used to join pieces of cardboard
   - what it means to have the strongest cardboard beam for the test
   - what it means to have the strongest steel beam for the apartment building

   Record the conditions for the test of your cardboard beam designs.

3. Write a statement identifying the problem for which you are designing a solution. You might also note how your solution fits into the design process for a larger problem.

4. Identify the criteria for a successful solution. Include any conditions for the test and any considerations related to the financial analyst's concerns that you interpret as criteria.

5. Identify the constraints that will impact the design of a successful solution. Include any conditions for the test and any considerations related to the financial analyst's concerns that you interpret as constraints. Make sure that you have identified all of the requirements and the stated desired properties of a solution as either criteria or constraints.

CONDUCT RESEARCH

Research different beam designs. What are common shapes for the cross-sectional area? What are other features you notice? From these existing designs, choose ideas that you can use or adapt in the design of your own beam.

DESIGN SOLUTIONS

Develop a plan for designing, testing, and optimizing a cardboard beam. For example, you might start by folding strips of cardboard or cutting flat shapes to explore how different cross-sectional designs behave. You might initially push or pull on them with your hands in order to determine the most promising designs. You might make small versions of several possible designs and test them using shorter spans. You might use binder clips, clothespins, or small bolts as rapid but temporary ways to hold pieces of cardboard together.

1. In your Evidence Notebook, record your plan for developing a design and building a cardboard beam to be tested. Your plan should include
   - materials you will need (include tools)
   - necessary safety procedures
   - a reasonable way to test several possible designs
   - an efficient way to keep records to support your decisions and to help you return to an earlier step
   - a schedule or timeline to ensure that you have enough time to build your final beam
2. Consult with your teacher. Once your plans are approved, begin to carry out your plan. You may find that you need to repeat parts of your plan. If you need or wish to do something very different than your approved plan, consult your teacher about the changes and required safety measures.

TEST

Use an iterative process in which you test designs and then make adjustments to one or more designs.

1. Beam designs intended for steel may not function the same way when made of cardboard, and they may function differently for different types of cardboard. Make preliminary tests on several designs. Use your results to judge how long to continue with several designs, when to settle on a single design, and when, if necessary, to reconsider a discarded design.
2. Test your final design to ensure it meets at least the minimum requirements.

OPTIMIZE

1. If you have several designs that are acceptable solutions, think about how much each design might be improved. Choose the best or continue with two designs if needed. Take into account the time and materials available to you.
2. Use the results of testing to improve your best design.
3. Think about how much time you would need to make a new sample of your best design. While you still have time to for either choice, decide whether to make a new sample or to use your working model.

LESSON 1: MOTION IN ONE AND TWO DIMENSIONS

In your Evidence Notebook, use diagrams and displacement vectors to show how a beam is deformed when a force is applied.

Answer the following questions in your Evidence Notebook:

1. Sketch the sample piece of cardboard that was tested. How would you use displacement vectors to show the effects of hanging weight on the sample?
2. What are possible frames of reference for measuring the deformation of the beam in response to an applied weight? What are the tradeoffs of measuring relative to a coordinate system on the beam or relative to the environment?
3. How might you use displacement to ensure that your tests don't weaken or break your full-sized working models?

LESSON 2: FORCE, MASS, AND ACCELERATION

In your Evidence Notebook, draw a free-body diagram for your cardboard beam with the initial weight added. Label all relevant forces.

Answer the following questions in your Evidence Notebook:

1. How much does a free-body diagram of the beam as a whole help you determine the best beam design? Explain your answer.
2. Draw a free-body diagram of just one point on the test sample or a beam design, such as a point where the string was attached. How does it change if the cardboard bends?
3. Where does your beam need to be strongest? How does that affect your design?

LESSON 3: ENGINEERING

Answer the following questions in your Evidence Notebook:

1. Your firm has chosen to break down the problem of supporting a building over a parking area. One step was to explore beam designs by using cardboard models. List at least two advantages and two disadvantages of breaking down the problem in this way. Then describe an alternative way the problem might have been broken down.
2. Review your research and tests to think about features that seem to make the most difference to the strength of a beam. Think about the criteria and constraints. Which tradeoffs do you think are the most important for the cardboard beam? Which tradeoffs do you think will be most important for the steel beam? Explain your answers briefly.

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DRAW CONCLUSIONS

Write a conclusion that addresses each of the points below.

Claim When you submitted a beam to be tested, you were making a claim that your design would be the best. Describe your beam design as your initial claim. Then make a new claim: As a result of the class tests, which beam design(s) should be submitted for further development?

Evidence What evidence supports your claim?

Reasoning Explain how the evidence you gave supports your claim. Describe in detail the connections between the evidence you cited and your claim.

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EXTEND

In the design of a steel beam for the building, costs include the amount of steel needed and the amount of welding or drilling needed. Assume that a beam with a simple open structure, such as a cross section shaped like a C or a T, can be made in one piece. A design similar to corrugated cardboard would need to be fastened (welded or drilled and bolted) where the folded and flat pieces come together. Decide on a rating system for each type of cost, such as a rating of 3 for a design that requires one weld along the full length. Do the same for the other required and desirable properties. A better design, such as one with a lower cost, should get a higher number.

Use a decision matrix to determine the best overall designs that should be taken to the next stage of development. You will need to set a relative importance (weight) for each criterion. You can use or adapt the sample matrix shown here.

Criterion	Weight	Beam design 1	Beam design 2	Beam design 3	Beam design 4
Strength					
Minimal steel					
Minimal welding					
Total points					

COMMUNICATE

Develop a presentation that describes your project, or participate in a group discussion. Be sure to include the evidence gathered to answer these questions:

1. How was the engineering design process used to reach an optimal solution?
2. How useful was it to test several designs, initially? Given the outcome in your particular case, would it have been just as good or more efficient if you had chosen one design without testing first?
3. How important was it, in this particular project, to use an iterative process of testing and adjusting the design(s)? As part of your answer, make a brief comparison of the initial design you thought was best and the final design.
4. What was good about the approach, and what should be done differently for another engineering design lab?